HALL MOBILITY OF TELLURIUM FILMS DEPOSITED ON $BaTiO_3$ CRYSTAL

A. K. CHOUDHURI AND S. K. DUTTA ROY

Department of Physics, Indian Institute of Technology, Kharagpur, India

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ABSTRACT. The measurements of electrical resistivity and Hall coefficient of tellurium films deposited on polarised barium titanate single crystals have been reported; the results on glass and mica substrate are also included for comparison. The results yield a value of surface state density for tellurium to be $15 \times 10^{14}/cm^2$ volt and the energy of the surface states 0.09 e.v. below the mid gap position.

INTRODUCTION

The surface properties of a semiconductor are generally determined from the field effect experiments on evaporated layers of films deposited on glass and mica substrate. It has been observed that if the thickness of the film is of the order of the space charge layer (10^{-4} to 10^{-5}cm), then with the application of a transverse electric field to the surface, part of the induced electric charge is trapped by the surface levels and other part changes the carrier density in the space charge region. At the same time an interaction between the space charge layer of the upper and lower surfaces introduces a large scattering of the carriers and the conductivity and Hall mobility of the film become less than the bulk value.

Recently Aigrain *et al* (1952), Godefroy (1956), and Ghosh (1961) have made detailed investigations of field effect of tellurium films deposited on mica and glass substrate. They have shown that there is a large decrease in field and Hall mobility with the decreasing thickness of the film and this is due to the inclusion of more defects in the thinner films. But it is quite noticeable that the field mobility measurement is more reliable. The changes in Hall mobility with transverse electric field (upto 500 volts/cm) are very small and almost of the order of experimental accuracy.

This paper reports the Hall effect and conductivity measurements of tellurium films deposited on a ferroelectric crystal instead of glass substrate. The film is exposed to intense localised electric field at the semiconductor substrate contact. This would materially affect the density and scattering of the carriers and the changes in Hall mobility would be very large, not only increasing the reliability and sensitivity of the measurements but also the effect of the ferroelectric property of the crystal would be reflected on the results and this property of the crystal could be easily observed if the polarization of the crystal is gradually increased to saturation. An experiment of this nature has as yet attracted limited attention.

EXPERIMENTAL

Tellurium films on $BaTiO_3$ substrate was prepared using a conventional vacuum coating apparatus. The thicknesses of the films were about 0.7μ and were determined by the graphical method (Nandi, 1954). The dimension of the films were $1.0 \times 0.5 \times 7.10^{-5}$ cm. As it is known that the adsorption of a gas on the surface of a semiconductor affects the surface barrier, causing large changes in surface conductance, the films were therefore removed to the experimental chamber within few minutes after preparation and aging of the films were done for more than twenty four hours until the constancy in resistivity was reached. In this way any contamination due to nitrogen and oxygen from air was precluded. The vacuum within the experimental chamber was as low as 10^{-4} to 10^{-5}mms. of mercury. A heater and a Cu-constantan thermocouple were provided in the experimental chamber in order to measure the temperature and also to keep the sample at different fixed temperatures of the bath.

The voltage and current measuring circuits were constructed following the standard circuit given by Pugh and Foner (1953). The Hall and resistive voltages were of the order of 100 microvolts; this was measured very easily with a microvolt potentiometer with a Liston-Becker chopper amplifier and a wide scale millivoltmeter as output meter. In this arrangement a voltage of the order of

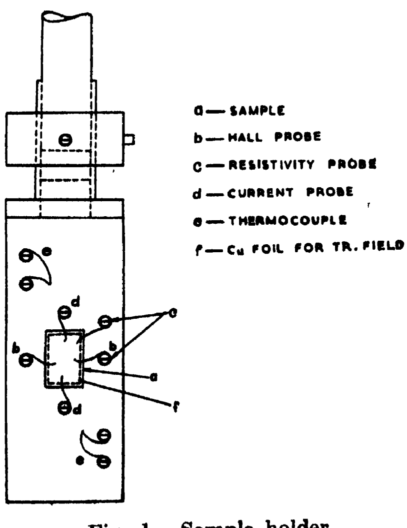


Fig. 1. Sample holder.

$0.1\ \mu V$ could be measured. In Hall effect measurement, always the special feature is the construction of a suitable sample holder; the major difficulty appears at the contact probes, which have a tendency to scratch out the film. After several preliminary trials this difficulty was finally removed by making a sample holder from syndanio board in which phosphor bronze springs were incorporated at predetermined distances (Fig. 1). These springs not only made automatic electrical contacts of current and Hall probes but also kept the sample rigidly in position. But for surity of good electrical contacts minute traces of aquadag were used at the contact points.

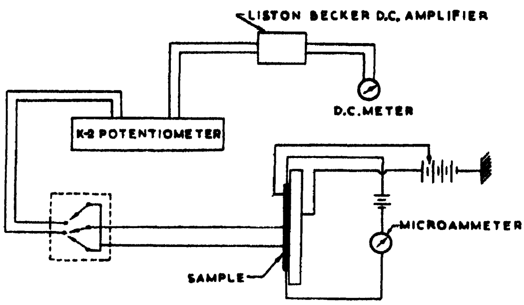


Fig. 2. Circuit diagram.

For field effect measurement (Fig. 2) a thin copper foil was placed underneath the flat face of $BaTiO_3$ crystal. This arrangement formed a parallel plate condenser with the tellurium film as the top plate and copper foil as the bottom plate with $BaTiO_3$ as dilectric. The electric field could then be applied across the crystal and polarisation of the crystal could be effected by increasing the electric

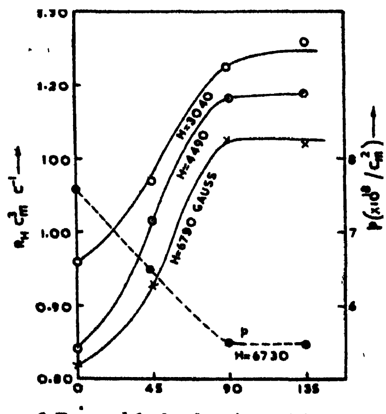


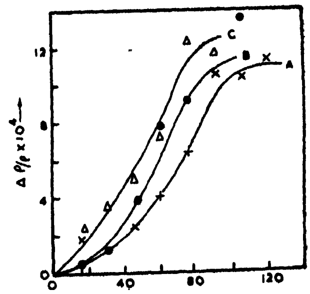
Fig. 3. Variation of R_H and hole density with transverse electric field.

field at a step of 15 volts upto 220 volts. Arrangements were also provided for depolarising the crystal so that fresh sets of measurements could be taken. The apparatus was standardised with spec pure (Johnson and Mathey) copper foil.

The Hall coefficient at 300°K was found to be -5.4×10^{-13} volt cm. amp^{-1} gauss.$^{-1}$. This is within one percent of the value quoted by Jan (1955). The electromagnet was of aircooled type and the maximum field for 1.5″ pole gap was limited to 8000 gauss. The magnet field was calibrated with a fluxmeter to within one percent.

RESULTS AND DISCUSSION

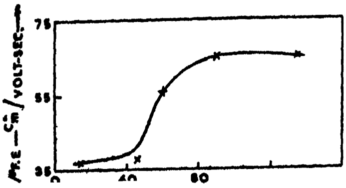
Fig. 3 shows the variation of Hall coefficient R_H and P (hole density/cm^2) as a function of the applied field. The number of carriers rapidly decrease with increasing polarisation of the crystal. The magnitude of Hall coefficient for films of tellurium on glass and $BaTiO_3$ substrates (deposited from the same p type bulk sample) of comparable thickness is different; R_H is larger in glass substrate almost by a factor of 1.5 (Godefroy's (1956) result with mica substrate is higher than the values of glass and $BaTiO_3$ substrate). This difference is due to the contact of three different dielectrics on the surface of tellurium; this contact difference modifies the structure of tellurium and perhaps the surface states are also altered.



E (In Volts) →

Fig. 4. Variation of $\Delta\rho/\rho$ with applied transverse electric field.

Fig. 4 shows the variation of resistivity with applied electric field. The curves A, B, C are obtained after depolarising the $BaTiO_3$ crystal in quick succession by applying transverse A.C. voltage. The curves are almost similar in nature,



Volts→

Fig. 5. Variation of field mobility with transverse electric field.

only the saturation field of the crystal is different by about 10 volts. The crystal comes back to its initial unpolarised condition after about twenty four hours.

The field mobility (Fig. 5) is calculated from the expression :

$$\mu_F = \frac{d\,\Delta\sigma}{dQ}$$

Where $\Delta\sigma$ is the change in conductivity per unit area of the surface and Q is the charge induced on the surface. dQ is found out from the measurement of applied voltage, dimension of the specimen and the capacity between the film and the field plate; the capacity is quite high in the present case because of the high dielectric constant of $BaTiO_3$ crystal. This is a particular advantage over the glass substrate samples, because the $BaTiO_3$ substrate introduces a reliability in the measurement of capacity which is a common source of error in field effect experiments. The field mobility increases at higher fields. The lowest value of field mobility is higher by a factor of three from the values quoted by Ghosh (1961) for glass substrate samples. The present values compare well with similar results on mica substrate (Godefroy, 1956).

The field mobility results can also be utilised in calculating the surface state density. Shockley and Pearson (1948) have shown that the surface state density of the films of a semiconductor is given by

$$N_s = 1.31\times10^{12}\left(\frac{\epsilon\mu}{LV\sigma}\right)^{\frac{1}{2}}\sigma\,\frac{\delta q}{\delta\sigma}$$

where the units are N_s/cm^2 volt, μcm^2/volt-sec, L cm, V in volts, and σ mhos, δq coulombs/cm^2, $\epsilon = 30.5$ for tellurium. N from the present results yields a value 15×10^{14}/cm^2. volt. This is about twenty times higher than the value for p-germanium quoted by Pearson and Shockley (1948). Our result is quite expected since tellurium is nearly metallic, so that the density of surface states should be higher than the corresponding value of p-Ge.

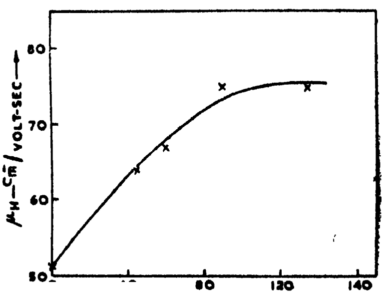


Fig. 6. Variation of Hall mobility with transverse electric field.

Fig. 6 shows the variation of Hall mobility μ with applied field. μ increases with increasing polarisation of the $BaTiO_3$ crystal. Hall mobility is also higher than the field mobility. Both these suggest that the increasing number of carriers are made to conduct in the space charge layer due to the large scattering of the carriers. It is also interesting to note that the magnetic field variation also shows a large change of R_H (Fig. 7). This variation is small in glass substrate; but in $BaTiO_3$ this variation increases with increasing polarisation of the crystal. The calculation of mean free path from Hall mobility data yields a value of 10^{-6} cm at 300°K. This is quite small in comparison to the thckness of the film and the size effect of the type suggested by Sondheimer (1950) is not expected. But the nature of magnetic field variation resembles Sondheimer's field variation curves

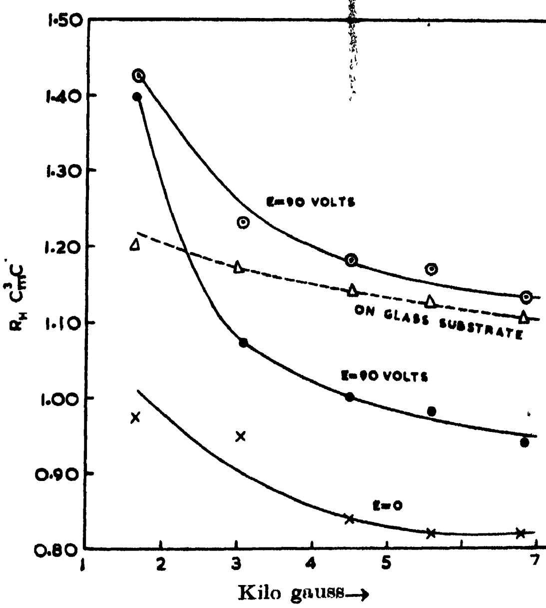


Fig. 7. Variation of R_H with H.

for diffuse scattering, though such a large magnitude of field variation (particularly at the saturation field of the crystal) is not accounted for on the basis of Sondheimer's theory alone. This result is at present not well understood.

The ratio μ_H/μ_F shows a slight variation almost of the order of experimental errors. Our value is smaller by a factor of three from the results quoted by

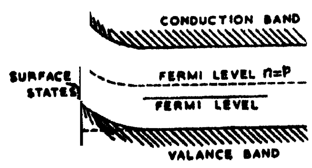


Fig. 8. Band representation showing position of the energy bands at the surface.

Ghosh (1961) on glass substrate. Using the expression for surface state energy as deduced by Godefroy[2] (1956) on the basis of discrete energy levels associated with the surface, the energy of the surface states η as measured from the mid gap position at the surface, yields a value 0.09 e.v. below the mid gap position (Fig. 8). This differs with the value of η in glass substrate as 0.10 e.v. and in mica 0.08 e.v. above the middle of the forbidden energy gap.

The ferroelectric loop of $BaTiO_3$ crystal is observed in Hall effect and conductivity results, particularly the onset of saturation beyond 90 volts is clearly indicated in Figs. 4 and 5. The conductance and Hall coefficient variations are proportional to the induced charge hence to the polarisation P; both R and $\Delta\sigma$ are therefore functions of polarisation.

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